Lunar Mapping using CLASS XRF data

Inter IIT Tech Meet 2024

Team 57

Inter IIT Tech Meet 13.0

December 13th, 2024

Outline

1. Introduction : Lunar X-Ray Fluorescence
2. Instrumentation and Line Broadening
3. Baseline Correction
4. Multiple Gaussian Fitting
5. Catalog Creation
6. Map Creation Methodology
7. Verification
8. Future Scope : Deep Learning assisted super resolution algorithms

Introduction to Lunar XRF Emission

- **How Lunar XRF Emission Occurs:**
  - High-energy solar X-rays excite atoms on the lunar surface.
  - Inner-shell electrons are ejected, leaving vacancies.
  - Electrons from higher shells transition to fill these vacancies, emitting secondary X-rays characteristic of specific elements.
- **Why Observe During Solar Flares:**
  - Solar flares significantly increase the intensity of solar X-rays.
  - Enhanced X-ray flux provides a stronger excitation of lunar surface atoms.
  - Results in higher signal-to-noise ratio for detecting XRF emissions, improving the precision of elemental abundance measurements.
- **Significance:**
  - Allows non-destructive mapping of key elements like Mg, Si, Al, Ca, Fe, and Ti.
  - Essential for understanding the Moon's geological composition and history.

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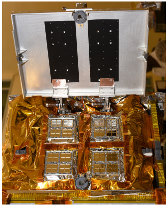
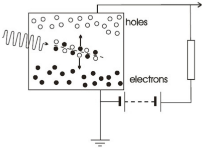
Instrumentation and line broadening

CLASS Instrument

The Chandrayaan-2 Large Area Soft X-ray Spectrometer (CLASS) uses swept charge devices (SCDs) to measure the Lunar XRF spectra.



(a) CLASS Instrument



(b) X-Ray Interaction

- Incident X-rays ionize the semiconductor, producing electron-hole pairs proportional to the energy of the incoming photon.
- An electric field directs the migration of electrons and holes to the electrodes, generating a measurable pulse in the outer circuit.

Spectral Artifacts: Peak Broadening

- XRF lines experience Gaussian peak-broadening, due to:
  - Statistical nature of photon-charge conversions
  - Electronic noise
- The Gaussian profile is given by:

$$G(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

- Incoming lines are not discrete but have a Lorentzian profile:

$$L(x) = \frac{\gamma}{\pi\left[(x - x_0)^2 + \gamma^2\right]}$$

- Spectral peaks follow a Voigt profile:
  - A convolution of a Gaussian and Lorentzian distribution
- The pseudo-Voigt approximation is often used:

$$V(x) = \eta L(x) + (1 - \eta)G(x)$$

where $0 \leq \eta \leq 1$ is the mixing parameter.

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Baseline Correction

- **Former Idea :** To add up the non flaring spectra by time just before the flaring events
  - Good Statistical Data
  - Smoothened Background estimation
  - Neutral to abnormal noise peaks
  - Not- Dynamical
- **Our Approach :** Moving Average Technique incorporated with The Former One
  - A dynamical way of base line correction
  - Preserves the signals along with active noise reduction
- **What changes did we make?**
  - The former approach stays same except a slight modification!
  - The noise weights of files without any signal gets added into the global noise to give a dynamical background for each file.
  - For example a single peak will add it's own weights into the global background, resulting in a better statistical picture.
  - Always better than a simple non flaring data addition.

Baseline Correction

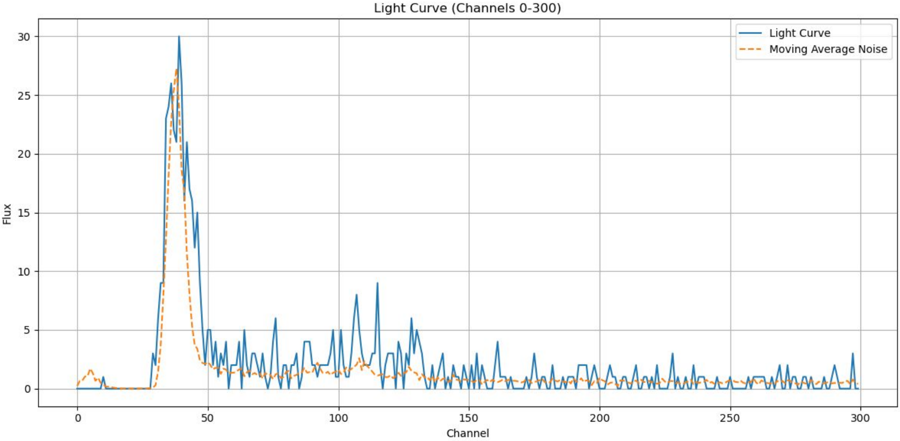

Figure: Baseline Correction using Moving Average Technique

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Multiple Gaussian Fitting

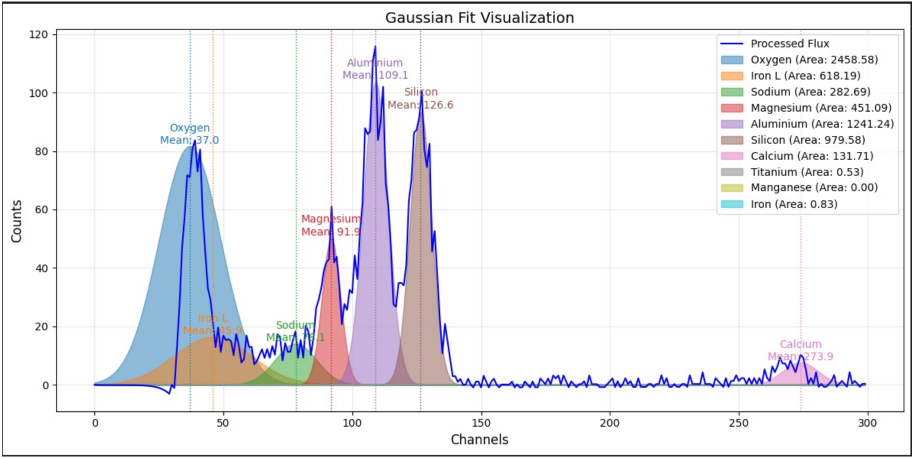

Figure: A Bad Gaussian Fitting

Multiple Gaussian Fitting

- **Lead-in** :
  - Multiple Mask Lengths : As different regions of spectrum influencing the fit differently
  - Effect of Mask Lengths : Larger mask length incorporates larger base line, whereas smaller one focuses on the peak only.
- **Approach**
  - Each element multiple masking regions choosen
  - Independent Gaussian fittings done
  - Fitting process should be adaptive to spectral context (Mean not deviating too much from the theoretical value)

Multiple Gaussian Fitting

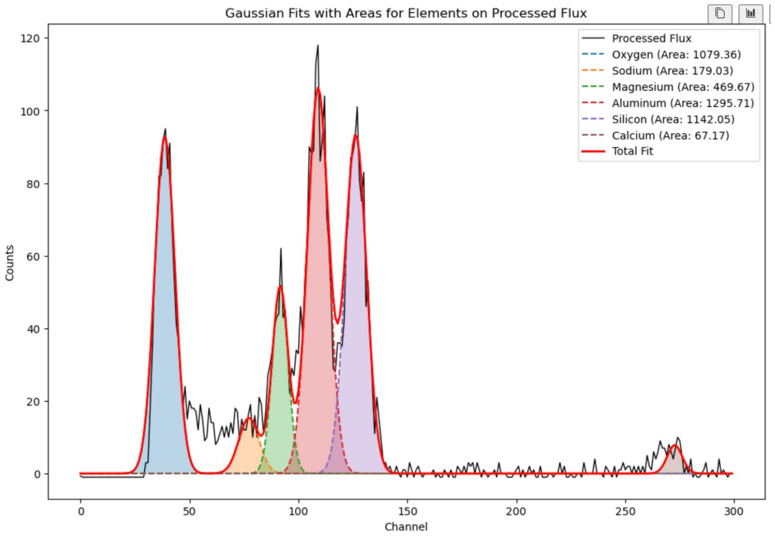

Figure: A good fit with minimal overlap

Multiple Gaussian Fitting

- **Challenges while Oxygen Spectral Fitting**
  - Large abnormal area under the Gaussian giving huge flux count
  - Presence of a big peak just before the Oxygen peak
  - Larger peak overshadows the behavior of smaller one
- **Solutions**
  - De-convolved Waves
  - Analytical Continuation
  - Iterative Refinement
  - Imposing Pre-existing Model (eg. X2Abundance Model)

Multiple Gaussian Fitting

- **Our Approach & Justification (Analytical Continuation)**
  - A huge difference in means can be seen before and after the oxygen peak.

$$G(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

  - Points after channel number 37 taken into account with a certain mean.
  - Analytically, the same mean was continued to the other side.

  Resulting fitting was found out to be free from the influence of larger peak.

- **Uncertainty Calculation due to Overlapped Area**

$$\Delta A = \sqrt{\left(\frac{A_{\text{overlap}}}{A_1}\right)^2 + \left(\frac{A_{\text{overlap}}}{A_2}\right)^2}$$

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Data Structure Explanation

- **Latitude and Longitude:**
  - Specifies the geographical boundaries of each $12.5 \times 12.5 \text{ km}^2$ grid.
  - Four columns represent the latitude and longitude of the grid's four corners.
- **Gaussian Fit Areas:**
  - Contains the area under the Gaussian fit for each detected element.
  - Represents the photon flux, which is directly proportional to the elemental abundance.
- **Uncertainties in Gaussian Fits:**
  - Quantifies the errors or deviations in the fitted Gaussian areas.
  - Accounts for factors like overlapping peaks and noise in the spectra.

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Coverage of the data

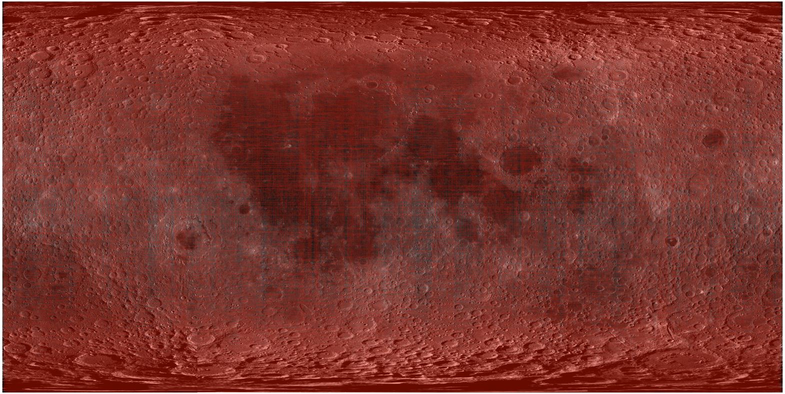
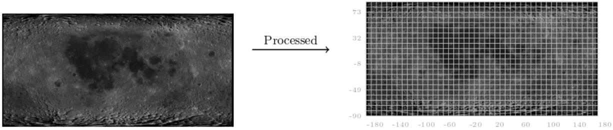


Figure: The coverage of the Lunar XRF CLASS data

Methodology for Map Creation

- **Sub-Pixel Resolution:**
  - The map is divided into smaller grids, each smaller than the resolution of the CLASS detector.
  - This approach enhances spatial resolution and achieves sub-pixel accuracy.
- **Weighted Averaging:**
  - For each smaller grid, a weighted average of intensities is calculated.
  - Intensity weights are derived from the overlapping areas of larger signal grids.



Original Image

Image with Grid

Figure: Discretizing the map into grid lines

Interactive and Heat Map

- **Interactive Map:**
  - Displays average elemental ratios for each small grid, calculated from the Gaussian fit.
  - Displays uncertainties involved in the calculation due to overlap and convolution of Gaussians.
  - Ratios are calculated with respect to silicon, based on its homogeneous distribution across the lunar surface as established in the literature.
- **Heat Map:**
  - Represents the ratio of the flux contribution of each element to the total flux.
  - Highlights the spatial distribution of elements of interest, such as aluminum (Al), silicon (Si), calcium (Ca), magnesium (Mg), and iron (Fe).

Interactive Map

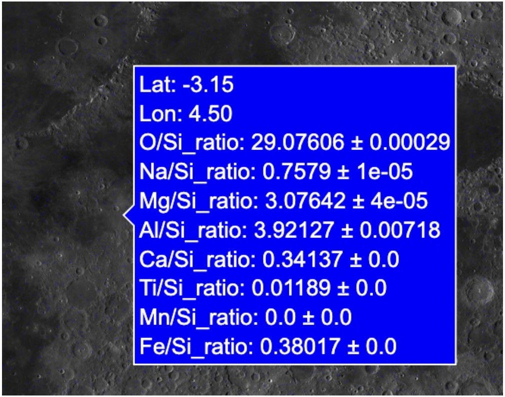


Figure: An Example of Interactive Map Attributes

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Results & Verification

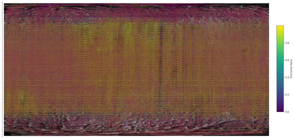
We have generated the heat maps for different element and there inbuilt co-relation verifies our work.

Geo Chemical Difference between Mafic and Felsic Rocks :

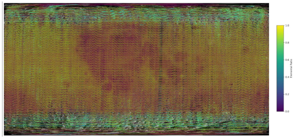
- Non-coexistence of Mg-Fe rich and aluminum rich rocks
- Proven by in-situ experiments and previous samples [1]
- Need to proof the same to show that our results are valid.

[1] The mafic component of the lunar crust: Constraints on the crustal abundance of mantle and intrusive rock, and the mineralogy of lunar anorthosite by Sarah T. Crites, Paul G. Lucey and G. Jeffrey Taylor

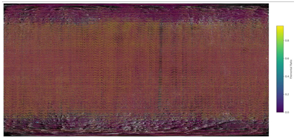
Heat Map Comparisons



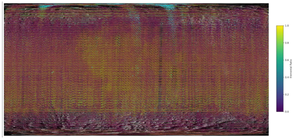
Magnesium



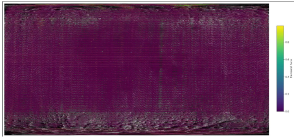
Aluminum



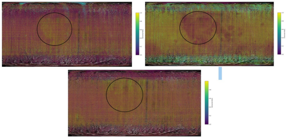
Silicon



Iron

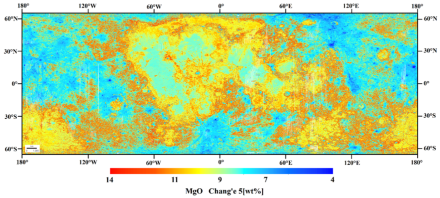


Calcium

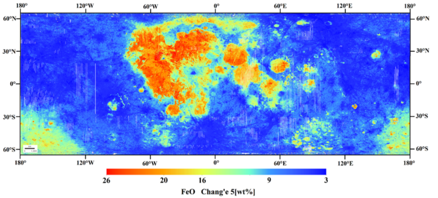


Fe-Al-Mg Correlation

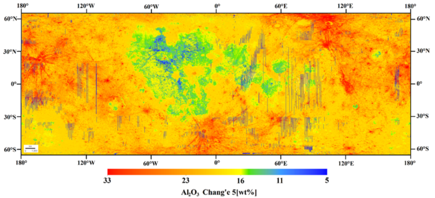
Results & Verification : Existing Maps



(a) Magnesium Coverage



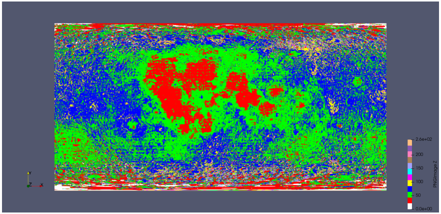
(b) Iron Coverage



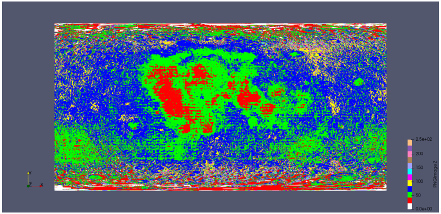
(c) Aluminum Coverage

Maps taken for veryfication from Comprehensive mapping of lunar surface chemistry by adding Chang'e-5 samples with deep learning by Chen Yang, Xinmei Zhang, Lorenzo Bruzzone, Jon Atli Benediktsson, Xin Ren, Haishi Zhao, Yanchun Liang, Bin Liu, Dawei Liu, Bo Yang, Minghao Yin6, Renchu Guan, Chunlai Li

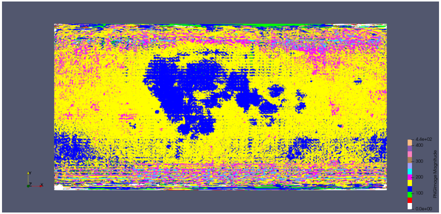
Our Results



(a) Magnesium Coverage

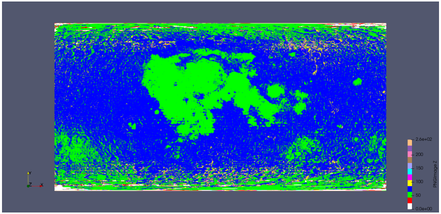


(b) Iron Coverage

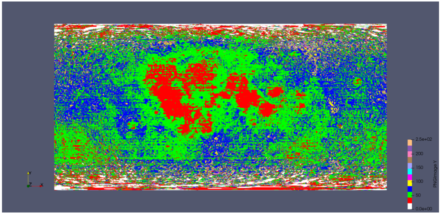


(c) Aluminum Coverage

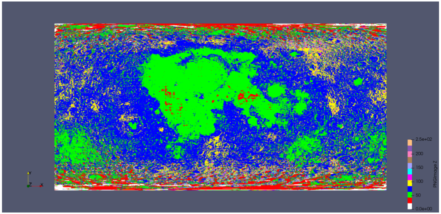
More Results !



(a) Silicon Coverage



(b) Sodium Coverage



(c) Calcium Coverage

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Future Scope

- **Integration of XRF Data:** Incorporate XRF-derived elemental abundances (e.g., Na, Mg, Al, Fe, Mn) with spectral and gamma-ray datasets for a comprehensive elemental mapping framework.
- **Enhanced Calibration:** Use XRF data to refine deep learning-based inversion models, improving mapping accuracy by addressing biases in optical-only data.
- **Multimodal Fusion:** Develop methodologies to combine XRF, optical, and gamma-ray data, focusing on complementary strengths of each modality.

Future Scope

- **Model Refinement:** Adapt the 1D CNN model to account for XRF spectral characteristics, enhancing predictions of surface chemical compositions.
- **Case Studies:** Apply enhanced mapping to critical regions like the South Pole-Aitken Basin, validating methods with existing ground truth (e.g., Apollo, Chang'e-5 samples).
- **Geochemical Insights:** Use XRF data to detect trace elements and subtle variations, improving understanding of lunar volcanic and magmatic evolution.

References

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